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Dan Bart
Director, Technical & Regulatory Affairs

TELECOMMUNICATIONS TIA INDUSTRY ASSOCIATION

October 22, 1993

William F. Caton, Acting Secretary
Federal Communications Commission
1919 M. Street, N.W., Rm 222
Washington, DC 20554

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Oct 22 '93
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OFFICE OF THE SECRETARY

Re: Ex Parte Presentation, PR Docket No. 93-61

Dear Mr. Caton:

On October 22, 1993, representatives of the Telecommunications Industry Association ("TIA") and the Electronic Industries Association Consumer Electronics Group ("EIA/CEG") met with representatives of the FCC's Private Radio Bureau. The attendees included:

Dan Bart, TIA, Director, Technical and Regulatory Affairs
Dr. Jay E. Padgett, AT&T, Chairman, TIA Mobile & Personal Communications Consumer Radio Section
Jim Haynes, Uniden, Chairman, TIA User Equipment Premises Equipment Division Standards Applications and Regulatory Affairs Section
Tom Mock, EIA, Director of Engineering Consumer Electronics Group
James Casserly, Squire, Sanders & Dempsey, Counsel. EIA/CEG
Ralph A. Haller, Chief, Private Radio Bureau
Beverly G. Baker, Deputy Chief, Private Radio Bureau
F. Ronald Netro, Engineering Asst., Private Radio Bureau
Richard J. Shiben, Chief, Land Mobile and Microwave Division, PRB

The purpose of the visit was to amplify on the points raised in TIA's Comments and Reply Comments filed in the referenced Docket regarding the current industry-wide investments that have been made in bringing new Part 15 products that operate in the 902-928 MHz band to the American public and to amplify on the interference potential those products could have on the new Automatic Vehicle Monitoring ("AVM")/Location and Monitoring Service ("LMS") being proposed by the Commission. As stated in TIA's pleadings, TIA supports the concept of the new AVM/LMS Service but has grave concerns about technical interference issues when millions of new Part 15 devices are deployed.

TIA supports spectrum for a permanent AVM/LMS but not at its current test bed location of 902-928 MHz. In other services such as Air-to-Ground, large-scale tests were accomplished in one area of spectrum and the permanent service was allocated different spectrum. If the use of 902-928 MHz is ultimately

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Representing the telecommunications industry in association with the Electronic Industries Association adopted for permanent AVM/LMS, the concerns of the Part 15 Industry and AVM/LMS parties need to be balanced so that millions of customers are not disadvantaged or provided with interference-prone services. EIA/CEG has already received reports of held orders since retailers are concerned with buying and selling products that an AVM/LMS licensee might try to have removed from service. It seems illogical to claim a service should be authorized because it is immune from interference from Part 15 devices and then request the use of such devices to be discontinued for causing interference. As noted in the NPRM, n. 50, such requests to discontinue use of Part 15 devices are occurring today.

Pursuant to Section 1.1206, attached are two (2) copies of the written presentation material discussed and a detailed Analysis of Teletrac Receiver Performance and Part 15 Interference prepared by Dr. Padgett. TIA agreed to contact Teletrac to inquire about pursuing a technical trial of the interference potential based on field conditions.

Respectfully submitted,

Dan Bart

Dan Bart

c: Ralph A. Haller, Chief, Private Radio Bureau
Beverly G. Baker, Deputy Chief, Private Radio Bureau
F. Ronald Netro, Engineering Asst., Private Radio Bureau
Richard J. Shiben, Chief, Land Mobile and Microwave Division, PRB

TELETRAC RECEIVER PERFORMANCE AND PART 15 INTERFERENCE

Outline

- Received power - desired signal (reverse link)
- Receiver power - Part 15 interference
- Carrier-to-interference ratio and Teletrac receiver characteristic
- Effect of receiver threshold and capacity vs. bandwidth
- Summary - conclusions:
  - Significant potential for interference from Part 15 to Teletrac.
  - Need for 8 MHz bandwidth per system is questionable, if receiver threshold is taken into account.

RECEIVED POWER - DESIRED SIGNAL

Hata model

- Fit to Okumura's data for macrocell mobile environment: $d \geq 1$ km, $h_B \geq 20$ meters.
- Gives median path loss vs. distance for specified antenna heights, frequency, environment (urban, suburban, rural).

Received power: $C = P_{TX} \cdot g_B a d^{-\gamma}$, or

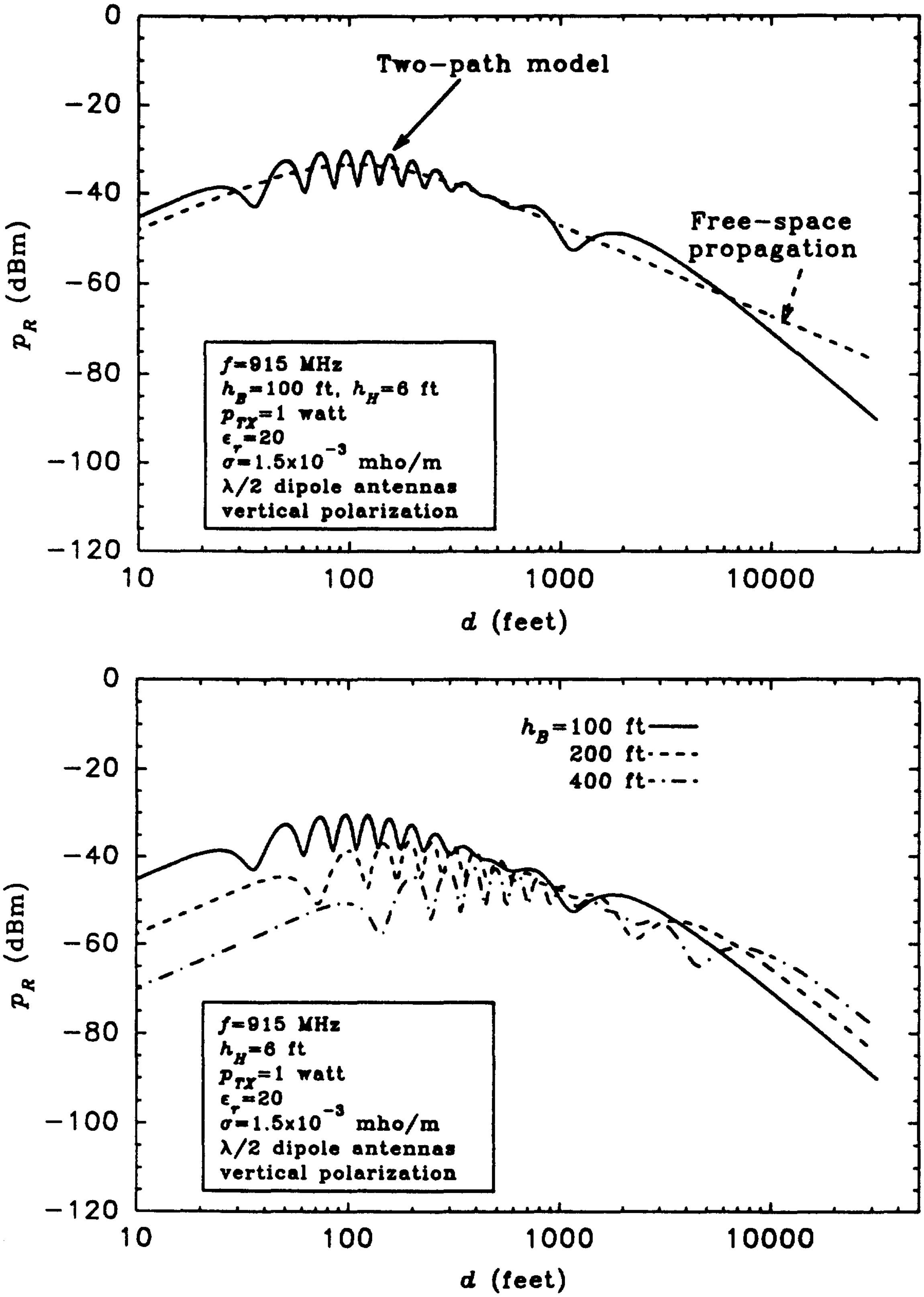
$$C\,(\mathrm{dBm}) = P_{TX}(\mathrm{dBm}) - \alpha - 10\gamma \log d + g_B(\mathrm{dB})\,,$$

where P_{TX} is ERP of the mobile, g_B is the gain of the base antenna, and α and γ given by Hata model; α depends on frequency, antenna elevations, environment, and γ depends on the antenna elevations.

With $P_{TX} = 30\,\mathrm{dBm}$ (1 watt), $f = 915$ MHz, and $g_B = 2.15\,\mathrm{dB}$ (half-wave dipole):

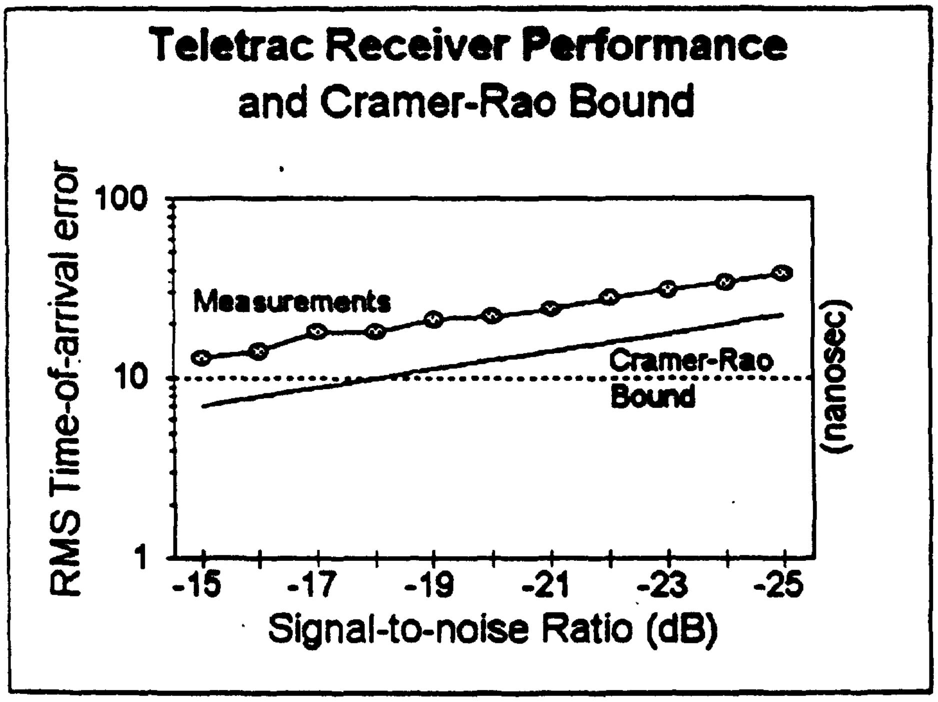
h_B(ft)	α (dB)	γ	C, dBm ($d = 5$ mi)
50	128.3	3.72	-122.1
100	123.7	3.52	-116.2
200	119.2	3.32	-110.2
300	116.5	3.21	-106.7
400	114.6	3.12	-104.3
500	113.1	3.06	-102.4

PART 15 INTERFERENCE



TELETRAC RECEIVER PERFORMANCE

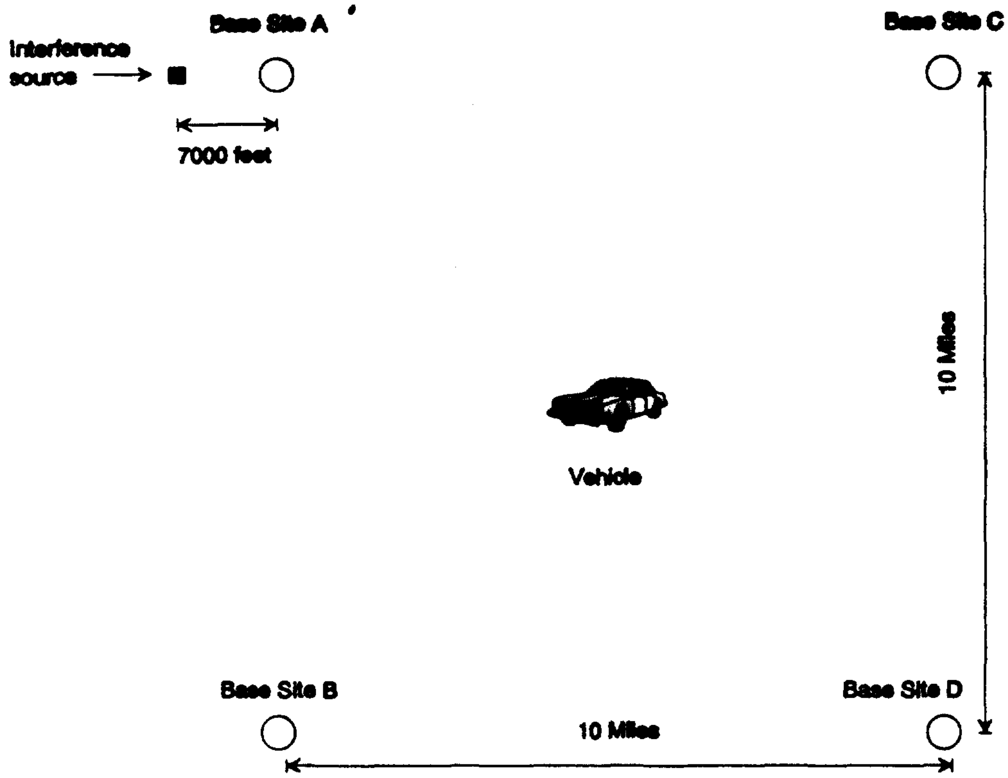
- σ_t is time-of-arrival (TOA) rms estimation error.
- For C/I (RF carrier-to-interference ratio) above threshold, $\sigma_t \sim 2/\sqrt{C/I}$ (follows Cramer-Rao bound with offset for "implementation loss" (about 5 dB).
- Threshold of current equipment is about -25 dB (carrier 25 dB *below* interference) due to spread spectrum processing gain.

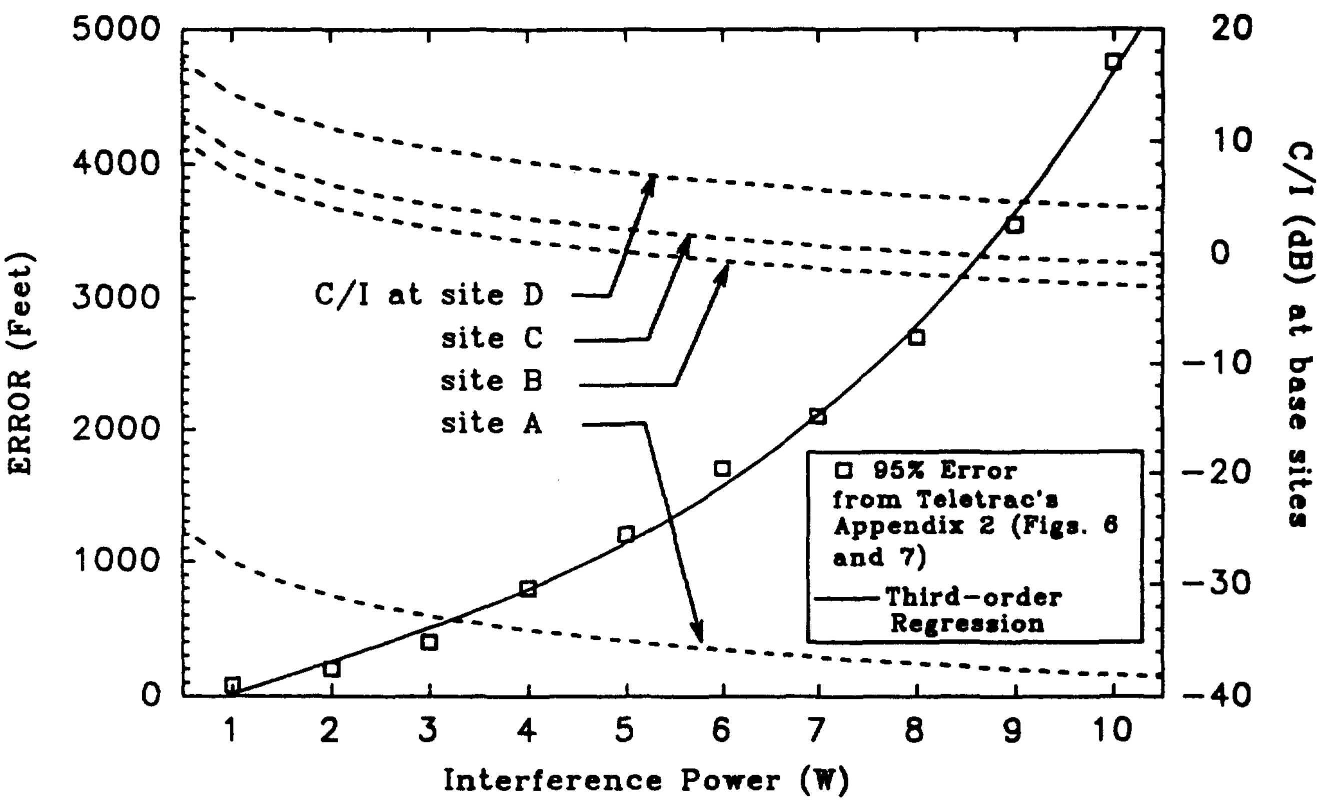


(reproduced from Appendix 2 of Teletrac's Comments, Fig. 12)

TELETRAC SIMULATION

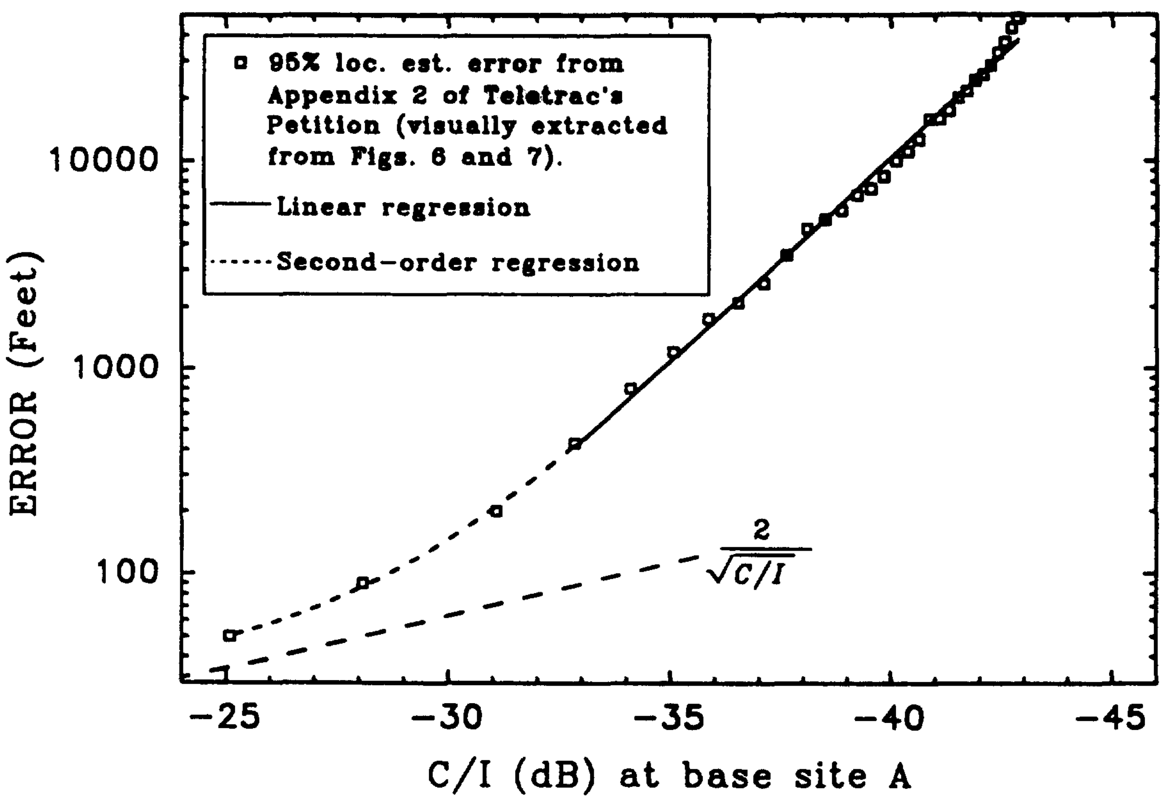
(from Appendix 2 of Teletrac's Petition)





TELETRAC RECEIVER BELOW THRESHOLD

(from Teletrac simulation results)



EFFECT OF RECEIVER THRESHOLD

$$\sigma_t^2 = \frac{k_a}{B^2(E/N_0)}, \quad E/N_0 \geq x_0.$$

σ_t = rms TOA estimation error

k_a = a constant that depends on the waveform and the receiver

B = noise bandwidth

E = energy in message; $E = CT$.

T = message duration

C = received RF carrier (desired signal)

N_0 = effective noise spectral power density (i.e., mW/MHz)

x_0 = receiver E_b/N_0 threshold

Note: $E/N_0 = BT \cdot C/N$ where N ($= N_0 B$) is the total noise power and BT is the "processing gain."

RECEIVER THRESHOLD (CONT'D)

Given C, x_0, and N_0 fixed, the value of T corresponding to threshold is:

$$T_0 = \frac{N_0 x_0}{C}.$$

The rms TOA estimation error then can be written as

$$\sigma_t^2 = \frac{k}{B^2(T/T_0)}, \quad T \geq T_0,$$

$$= \frac{k}{B^2(T/T_0)^4}, \quad T < T_0.$$

Let σ_0 be the target value of σ_t at threshold $(T/T_0 = 1)$. The bandwidth required to achieve this target accuracy is:

$$B_0 = \frac{\sqrt{k}}{\sigma_0}.$$

CAPACITY/BANDWIDTH TRADEOFF

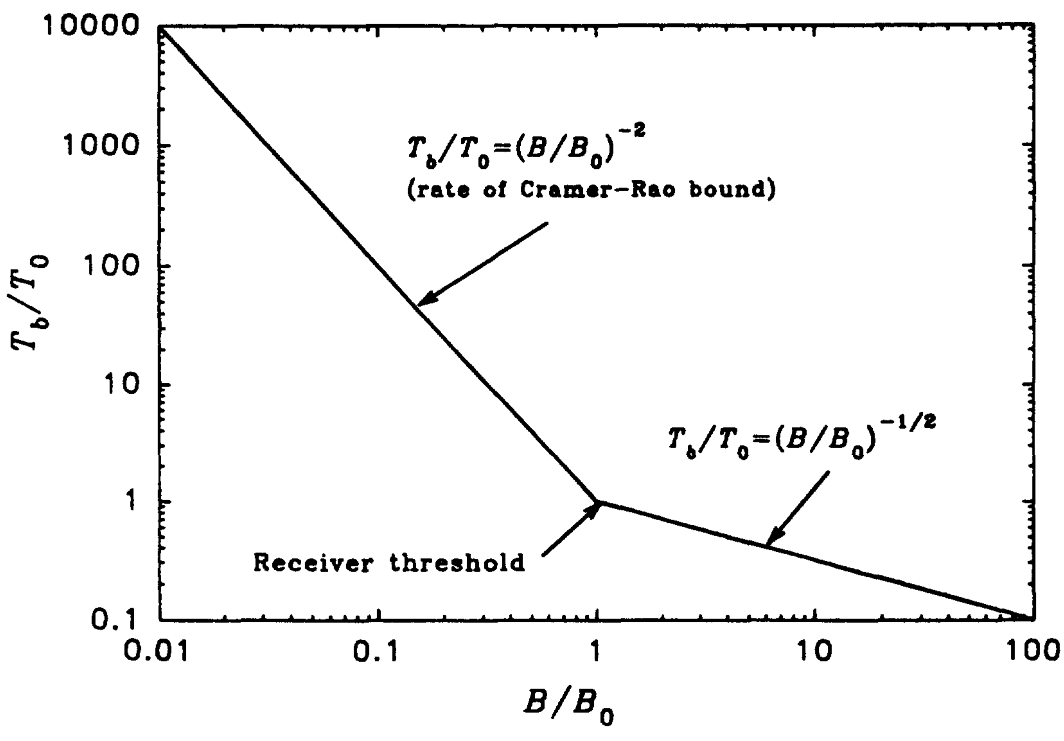
$$\frac{\sigma_t}{\sigma_0} = \frac{1}{(B/B_0)\sqrt{T/T_0}}, \quad T \geq T_0 .$$

$$= \frac{1}{(B/B_0)(T/T_0)^2}, \quad T < T_0 .$$

Once the bandwidth is sufficiently large to give the necessary accuracy at end-of-range (receiver threshold), the "tradeoff" between B and T is

$$T/T_0 = (B/B_0)^{-1/2}, \quad T < T_0 .$$

Conlusion: The "bandwidth squared" capacity gain is illusory. The real tradeoff is between capacity and base station coverage area (larger T allows lower C and hence greater range).



SUMMARY

Technical Conclusions

- Part 15 devices in the 902-928 MHz band pose a serious interference threat to wideband pulse-ranging AVM systems such as Teletrac's.
- The need for 8 MHz of bandwidth per system is questionable; the argument that capacity increases as the square of bandwidth is flawed because it does not account for the receiver threshold.
  - The necessary bandwidth is determined by the rms TOA estimation error required at end-of-range; it can be determined independent of message duration, assuming end-of-range is related to the receiver threshold.
  - For the current-generation Teletrac receiver, $\sigma_0 \sim 35$ nanosec, which corresponds to a ranging error of about 35 feet. Either with or without multipath, there seems to be little point in improving this.
  - The same accuracy could be achieved with less bandwidth by using a waveform better-suited to ranging.

Implications

- With its potential for uncontrolled interference, 902-928 MHz does not appear well-suited for a system such as Teletrac's. If the public need justifies it, perhaps another band should be sought.
- The spectrum requirements may not be as great as has been assumed. With an optimum ranging waveform design, less than 4 MHz per system might be adequate.

ANALYSIS OF TELETRAC RECEIVER PERFORMANCE AND PART 15 INTERFERENCE

Dr. Jay E. Padgett
Chairman, TIA Mobile & Personal Communications
Consumer Radio Section

October 22, 1993

EXECUTIVE SUMMARY

The FCC has adopted an NPRM in PR Docket 93-61, proposing to establish permanent provisions under Part 90 of its Rules for Automatic Vehicle Monitoring (AVM) systems in the 902-928 MHz ISM band. This proposal was made in response to a Petition filed in 1992 by PacTel Teletrac, which operates a wideband pulse-ranging AVM system in several metropolitan areas under the existing interim Part 90 Rules. The function of this system is to locate vehicles using a multilateration technique, whereby the vehicle responds to a narrowband high-power paging signal (the forward link) by transmitting a short (10-20 milliseconds) low-power wideband burst (the reverse link). This burst is received by multiple Teletrac base station receivers, each of which estimates the relative time of arrival (TOA) of the signal. Using the TOA estimates from the receivers and knowledge of their positions, the system can compute the location of the vehicle within several hundred feet.

One potential problem with this system is its vulnerability to interference from the unlicensed Part 15 devices that will be increasingly prevalent in this band. The purpose of this paper is to present an analysis of that interference and its effect on the Teletrac base station receivers. Teletrac contends that this interference will not present a problem to its system, but the analysis presented here shows otherwise. While the received signal power from a vehicle several miles from the base station will be on the order of -100 dBm (more or less depending on the base antenna elevation and the distance to the vehicle), the interference power from a Part 15 device several thousand feet from the base can be in the range of -40 to -60 dBm. The Teletrac receiver uses direct sequence modulation (a spread spectrum technique), which provides a processing gain that allows the receiver to operate satisfactorily with carrier-to-interference ratios as low as -25 dB (i.e., the desired signal 25 dB *below* the interference at the receiver). However, in the presence of interference that exceeds the desired signal by 40 dB or more, the receiver is operating far below its threshold and the TOA estimation error is so large that the receiver is essentially useless in contributing to the location estimate.* Widespread deployment of Part 15 devices, which are randomly located and uncontrolled,

* The simulation results reported by Teletrac in its Petition suggest that with a -40 dB carrier-to-interference ratio, the TOA estimation error can exceed 1 mile.

clearly could have a devastating effect on the performance and reliability of the Teletrac system.

The analysis provided here shows further that the relationship between bandwidth and capacity claimed by Teletrac and used to support the need for an 8 MHz reverse-link bandwidth is flawed. Teletrac claims in its Comments and Reply Comments that, based on the Cramer-Rao bound, which gives the theoretical lower limit on TOA estimation error, the required message length is inversely proportional to the square of the bandwidth, so that if the bandwidth is doubled, the message length can be reduced by a factor of four, quadrupling capacity. This claim, however, fails to account for the effect of the receiver threshold, and therefore is unrealistic.

As shown in this paper, the simulation results reported by Teletrac in its Petition, taken together with the receiver characteristic disclosed in Teletrac's Comments, suggest that once the receiver has reached its threshold, the minimum message duration varies as the inverse square root, rather than the inverse square, of the bandwidth. Consequently, to double the capacity, the bandwidth must be increased by a factor of four. Increasing the bandwidth from 4 MHz to 8 MHz will increase capacity by only about 40% (whereas capacity could be doubled by operating two systems on separate 4 MHz bands). Moreover, the Part 15 interference problem identified here cannot be solved even by increasing the bandwidth and holding the message length constant (thereby increasing the processing gain).

It is concluded that Part 15 devices represent a potentially serious threat to the viability of wideband pulse-ranging systems operating in the 902-928 MHz band, and regardless of the severity of the threat from Part 15 devices, increasing the bandwidth to gain capacity is not a worthwhile tradeoff. These conclusions imply that (1) the 902-928 MHz band, with its high potential for uncontrolled interference, may not be the appropriate band for wideband pulse-ranging systems such as Teletrac's, and (2) that 8 MHz per system may not be necessary in any event. These two points in turn suggest that another band should be sought for those systems, and the spectrum requirement may not be as great as has been assumed.

ANALYSIS OF TELETRAC RECEIVER PERFORMANCE AND PART 15 INTERFERENCE

1. INTRODUCTION

This paper presents an analysis of the potential for interference from Part 15 devices that operate in the 902-928 ISM (Industrial, Scientific, and Medical) band into the the receivers used by Pactel Teletrac's wideband pulse-ranging system. Those receivers are designed to estimate the relative time-of-arrival (TOA) of a signal pulse from the vehicle to be located. The TOA estimates from multiple receivers at different locations then are used by the central system processor to estimate the location of the vehicle via multilateration.

The focus of this paper is the performance of an individual receiver operating in the presence of cochannel interference. The objective is to develop an understanding of the degree to which Part 15 devices can corrupt the TOA estimate of an individual receiver. Section 2 reviews the fundamental theoretical limit on the TOA estimation error (the Cramer-Rao bound) as well as the measured performance of the Teletrac receiver. Section 3 analyzes the receiver threshold effect and its implications on the ability to improve system throughput by increasing the bandwidth. Section 4 discusses propagation and the signal power received by the base stations from both the desired transmitter and from interfering Part 15 transmitters. Section 5 discusses the conclusions.

Reference is made to Teletrac's Petition [1] as well as the Comments [2] and Reply Comments [3] that Teletrac filed with the FCC in response to the NPRM on PR Docket 93-61 [4], and to the technical Appendices of [1] and [2].

2. TOA ESTIMATION ERROR FOR RECEIVER OPERATING ABOVE THRESHOLD

2.1 The Cramer-Rao Bound

The receiver must provide an estimate of the TOA of a received signal burst. The measure of how effectively it does this is the rms TOA estimation error, denoted here by σ_t. As discussed in Appendices 1 and 2 of Teletrac's Comments, and also in the literature [5][6], the minimum mean-squared TOA estimation error is given by the Cramer-Rao bound as

$$\sigma_t^2 \geq \left[\beta^2 2E/N_0\right]^{-1}, \tag{1}$$

where E is the total received energy in the message, $N_0/2$ is the two-sided noise spectral power density, and β is the "effective bandwidth" or "Gabor bandwidth", given by

$$\beta^2 = \frac{\int_{-\infty}^{\infty} \omega^2 \, | S(\omega) |^2 d\omega}{\int_{-\infty}^{\infty} | S(\omega) |^2 d\omega} . \tag{2}$$

$S(\omega)$ is the equivalent baseband signal spectrum (i.e., the Fourier transform of the signal). If the occupied bandwidth is limited to W Hz, then the integrals in (2) would be taken between $-W/2$ and $W/2$.

If C is the received RF carrier (desired signal) power and T is the message length, then $E = CT$. As noted by Teletrac in Appendix 2 of its Comments[1] spread spectrum (direct sequence modulation) is used. This is to give a short pulse rise time without reducing the energy per message ("E" in eq. 1).

Assuming that cochannel interference has the same effect on receiver performance as additive Gaussian noise of the same total power,[2] and B is the receiver noise bandwidth, then by definition $N_0 = N/B$, where N is understood to be the total thermal noise plus cochannel interference power as seen by the receiver. Letting T_C denote the chip duration, and defining $k_{BT} \triangleq BT_C$ (a constant which depends on the modulation and the degree of sidelobe truncation in the frequency domain[3]), (1) can be written as

$$\sigma_t^2 \geq \frac{T_C}{2k_{BT}\beta^2 T(C/N)} , \tag{3}$$

where C/N is the RF carrier-to-noise ratio.

Letting $k_\beta \triangleq \beta/B$, (3) becomes

1. "Theoretical and Field Performance of Radiolocation Systems," PacTel Teletrac, June 25, 1993, Appendix 2 of Teletrac's Comments [2].
2. With a spread spectrum system, this is a reasonable assumption for purposes of analysis, because the receiver correlates the received signal with the high-rate "pseudonoise" (PN) code waveform, which collapses the desired signal to its information bandwidth but spreads the interference over the entire spread bandwidth, and randomizes it.
3. This depends on the filtering of the received signal.

$$\sigma_t^2 \geq \frac{T_C}{2k_{BT}k_\beta^2 B^2 T(C/N)} . \tag{4}$$

Clearly, $k_{BT}k_\beta = \beta T_C$, which is the same as the parameter "a" given in Appendix 2A of Teletrac's Comments.[4]. With $R = 1/T_C$ (the chip rate), (4) can also be expressed in the form of eq. A24 of Teletrac's Appendix 2A as

$$\sigma_t^2 \geq \frac{T_C}{2(k_{BT}k_\beta)^2 RBT(C/N)} . \tag{5}$$

2.2 Teletrac's Receiver Performance

Teletrac's Petition and Comments suggest the following system parameters: R = 1.7 Mchip/s, $T \approx 14$ milliseconds (70 messages/second), and $k_{BT}k_\beta = 1.875$ (corresponding to "Phase-shaped" BPSK modulation, from Table 1 of Teletrac's Appendix 2A).[5] Assuming $B = 2R$ (which appears consistent with eq. A25 of Teletrac's Appendix 2A), the Cramer-Rao bound on σ_t for the Teletrac receiver would be roughly $\sigma_t \geq 1/\sqrt{C/N}$ (nanoseconds). This is close to (but slightly below) the "Cramer-Rao bound" curve shown in Figure 12 of Teletrac's Appendix 2, reproduced here as Fig. 1. The curve representing Teletrac's measured receiver performance is roughly described by

$$\sigma_t \approx \frac{2}{\sqrt{C/N}} \text{ (nanosec)} . \tag{6}$$

Thus, the receiver's actual performance is about 6 dB worse than the Cramer-Rao bound calculated from the parameters estimated above, and about 5 dB worse than the "Cramer-Rao bound" curve in Fig. 1. It should be noted, however, that even the Cramer-Rao bound is design-dependent, because of the parameter k_β, which depends on the spectral shape of the

4. "Impact of Wide-band Co-channel Interference on the Accuracy of Hyperbolic Location," prepared by Emmanuel Wildauer, PacTel Teletrac, June 22, 1993, Appendix A to Appendix 2 of Teletrac's Comments [2].

5. The integration limits used to compute the values of $k_{BT}k_\beta$ for various modulation formats in Table 1 of Teletrac's Appendix 2A were not stated.

transmitted waveform.

3. THE EFFECT OF THE RECEIVER THRESHOLD

3.1 Mathematical Model

As noted in Appendix 1 of Teletrac's Comments,[6] the performance of the receiver follows the form of the Cramer-Rao bound only as long as the carrier-to-noise ratio is above some threshold. This receiver threshold effect limits the ability to increase capacity (reduce message duration) by increasing the bandwidth. To understand this limitation, (1) can be written as

$$\sigma_t^2 = \frac{k_R}{2\beta^2 n \cdot [f(E_b/N_0)]} , \tag{7}$$

where k_R represents the effect of receiver non-ideality during normal operation (i.e., a fixed dB offset from the Cramer-Rao bound). The parameter n represents the number of information bits in the message,[7] and E_b is the energy per bit, so $E = nE_b$. The function $f(\cdot)$ is defined as:

$$\begin{aligned} f(x) &= x \,, \quad x \geq x_0 \\ &= f_2(x) \,, \quad 0 < x < x_0 \end{aligned} \tag{8}$$

where $f_2(\cdot)$ is some unknown function and x_0 is the E_b/N_0 threshold, below which receiver performance no longer adheres to the form of the Cramer-Rao bound. For continuity, $f_2(x_0) = x_0$.

It is useful to normalize by defining a second function $g(\cdot)$ as

6. "Engineering Analysis of Cochannel Pulse-Ranging LMS Systems," Professor Raymond Pickholtz, June 28, 1993, Appendix 1 of Teletrac's Comments [2].
7. For a pure locating application (no information transmitted), $n = 1$. Eq. (7) presumes that for $n > 1$, a TOA estimate is generated for each received bit, then the n estimates are averaged to yield an aggregate estimate. The variance of n independent estimates will be less than that of each individual estimate by a factor of n.

$$g(\xi) \triangleq \frac{f(x_0\xi)}{x_0}, \tag{9}$$

hence, $f(x) = x_0 g(x/x_0)$. It is clear from (8) that for $\xi \geq 1$, $g(\xi) = \xi$ and for $\xi < 1$, $g(\xi) = g_2(\xi) \triangleq f_2(x_0\xi)/x_0$.[8]

If T_b is the duration of a bit, then $E_b = CT_b$ (the total message duration is $T = nT_b$). Since the objective here is to explore the limitations on trading-off the bandwidth B against the message duration T, it will be assumed that C, N_0, and n are fixed. If T_0 represents the bit duration for which the receiver operates exactly at threshold, then by definition

$$T_0 = \frac{N_0 x_0}{C}. \tag{10}$$

Letting $\beta = k_\beta B$ as before, and aggregating fixed factors into a single constant, (7) becomes

$$\sigma_t^2 = \frac{k}{B^2 n[g(T_b/T_0)]} \tag{11}$$

where

$$k \triangleq \frac{k_R}{2k_\beta^2 x_0}. \tag{12}$$

Letting σ_0 represent the maximum acceptable value of σ_t, (11) gives

8. This is valid for any $f_2(x)$ for which a power series expansion exists; if $f_2(x) = \sum_{i=0}^{\infty} a_i x^i$ then $g_2(\xi) = \sum_{i=0}^{\infty} b_i \xi^i$, with $b_i = a_i x_0^{i-1}$.

$$g(T_b/T_0) = \frac{k}{B^2 n \sigma_0^2} . \tag{13}$$

If B_0 is the bandwidth for which $\sigma_t = \sigma_0$ when the receiver is operating at threshold (i.e., $T_b = T_0$), then from (13), with $g(T_b/T_0) = 1$,

$$B_0^2 = \frac{k}{n \sigma_0^2} . \tag{14}$$

Hence, (13) can be written as

$$g(T_b/T_0) = \left(\frac{B}{B_0}\right)^{-2} . \tag{15}$$

For $T_b \geq T_0$, $g(T_b/T_0) = T_b/T_0$ and (15) gives the relationship that T $(= nT_b)$ decreases inversely with B^2, used by Teletrac to argue that maximum capacity (messages per second) increases as the square of the bandwidth (see, for example, p. 21 of Appendix 1 to Teletrac's Comments). However, for $T_b < T_0$, $g(T_b/T_0)$ behaves differently. To understand the effect of increasing bandwidth when $T_b < T_0$, the behavior of $g(\xi)$ for $\xi < 1$ must be understood.

This behavior can be inferred from the first analysis provided by Teletrac in Appendix 2 of its Petition for Rule Making,[9] and the receiver performance curve provided by Teletrac in Appendix 2 of its Comments (Fig. 1 of this paper). In the first analysis of Appendix 2 of its Petition, Teletrac illustrated the effects of cochannel interference with an idealized example. As shown in Fig. 2, the vehicle to be located was positioned at the center of a square 10 miles on a side, and a receiver base station was on each corner of the square. An interference source was 7000 feet to the left of the upper left base station (designated "site A" for purposes of this discussion). Teletrac computed the location error at the 95th percentile as a function of the RF power radiated by the interference source. A 5 watt transmit power with an antenna gain of -6 dBi was assumed for the vehicle, giving an ERP of 1.25 watts. Path loss

9. "Impact of Co-channel Interference on 900 MHz Wideband Pulse-ranging AVM System Performance," PacTel Teletrac, April 6, 1992, Appendix 2 of Teletrac's Petition [1].

was taken to vary as d^4 (i.e., 12 dB per octave or 40 dB per decade), and fading effects (multipath, shadowing) were ignored. Specific system parameters such as base tower height, chip rate, receiver noise bandwidth/noise figure, and message duration were not disclosed. However, it was stated that the cochannel interference source was assumed to be at ground level (presumably representing a mobile unit).

Based on the information available, the C/I at each base station can be computed as a function of the RF power transmitted by the interference source, as shown in Figure 3.[10] Since the C/I at the other 3 sites is much higher than site A, those receivers should contribute negligible error (several feet or less) to the location estimate, assuming that Teletrac's analysis used the receiver characteristic reported in Appendix 2 of its Comments.

It thus appears that site A is dominating the overall location estimation error. If this is the case, the location error vs. the C/I at site A should accurately reflect the ranging error vs. C/I performance of a single receiver. Fig. 4 shows the location error from the study in Teletrac's Petition vs. the C/I at site A.[11] Also shown on Fig. 4 is the plot of $\sigma_r = 2/\sqrt{C/I}$ feet (dashed), which represents the rms ranging error (in feet) for Teletrac's receiver operating above threshold (i.e., $T > T_0$). The offset between the σ_r curve and the location error curve presumably occurs because the error curve represents the ninety-fifth percentile, while the σ_r curve represents the standard deviation of the estimation error. For most distributions, the ninety-fifth percentile will be more than one standard deviation above the mean (assuming an unbiased estimator, the mean is zero in this case).

The regression curve shown is actually the concatenation of a second-order regression (dashed) through the lower four points and a linear regression (solid) for all points except the lower three. This curve suggests that the receiver behaves in accordance with Fig. 1 provided C/I is above a threshold of roughly -25 dB. As C/I drops below -25 dB, the error begins to increase more rapidly than the inverse square-root of C/I. Once C/I drops below about -30 dB, the error vs. C/I characteristic becomes roughly inverse-square; that is, $\sigma_r \propto (C/I)^{-2}$. Thus, σ_t varies as $1/\sqrt{C/I}$ for $C/I \geq -25\,\text{dB}$, and as $1/(C/I)^2$ for $C/I < 30\,\text{dB}$. The range $-25\,\text{dB} > C/I > -30\,\text{dB}$ is a transition region between the inverse square-root and inverse square variations. During discussions with Teletrac representatives [9], it was confirmed that a C/I of -25 dB is roughly the practical lower carrier-to-noise limit of operation for the receiver.

This suggests that $f_2(x)$ can be modeled as $f_2(x) = x_0(x/x_0)^4$, so $g_2(\xi) = \xi^4$. Using this model for $g_2(\xi)$, (15) gives the tradeoff between T_b and B as

10. Fig. 3 is the same as Fig. 1 of the TIA Consumer Radio Section's Comments [7].

11. Fig. 4 is a modified version of Fig. 2 of the TIA Consumer Radio Section's Reply Comments [8].

$$T_b/T_0 = (B/B_0)^{-2}, \quad T_b \geq T_0 \tag{16a}$$

$$T_b/T_0 = (B/B_0)^{-1/2}, \quad T_b < T_0 . \tag{16b}$$

Hence, the bandwidth-squared capacity increase applies only for $B \leq B_0$, and capacity cannot be increased as B^2 indefinitely. For $B > B_0$, the rate of increase slows to a square-root law, at which point it clearly is more efficient to increase capacity by using two separate frequency bands. Fig. 5 shows a piecewise-log-linear plot of T_b/T_0 vs. B/B_0.

3.2 Receiver Threshold - Summary and Implications

The results just derived may be summarized as follows:

1. The value of T_b for which the receiver operates exactly at threshold is T_0, given by (10) as $T_0 = N_0 x_0/C$. Reducing T_b below T_0 (assuming N_0, x_0, and C are fixed) will cause E_b/N_0 to drop below the threshold x_0, whether or not the bandwidth is increased.

2. The required bandwidth for an rms TOA estimation error of σ_0 when the receiver is operating at threshold (i.e., $E_b/N_0 = x_0$) is given by (14) as $B_0^2 = k/n\sigma_0^2$, where $k = k_R/2k_\beta^2 x_0$, $k_\beta = \beta/B$ (which depends on the shape of the desired signal spectrum), and n is the number of information bits in the message. For a pure locating application, $n = 1$. For Teletrac's receiver, $\sigma_0 \approx 35$ nanosec for $C/I = -25$ dB, which appears to be the threshold for Teletrac's current-generation receiver parameters.

3. Given T_0, x_0, and σ_0 constant, B can be traded off against T_b according to (16a) and (16b). However, to decrease T_b below T_0, B/B_0 must increase as the square of T_0/T_b. Thus, from a spectrum-efficiency perspective, it does not pay to increase B above B_0. An increase in bandwidth to improve accuracy seems equally unjustified. Doubling the bandwidth of Teletrac's system would presumably decrease the rms TOA estimation error at threshold from about 35 nanoseconds to about 18 ns (i.e., an improvement in rms ranging error from 35 feet to 18 feet) in the absence of multipath, which seems to be past the point of diminishing returns. For the real-world environment in which Teletrac's system typically must operate, this improvement would be completely overshadowed by the uncertainties introduced by multipath. Without multipath, 35-foot accuracy would seem to be better than adequate. Hence, in either case, there seems to be no good reason to increase the bandwidth.

In light of these relationships, the "bandwidth squared" capacity increase claimed by Teletrac (see, for example, pp. 31-32 of Teletrac's Comments and p. 25 of Teletrac's Reply Comments) is illusory. If base stations are located to take maximum advantage of their operating range (that is, $E_b/N_0 = x_0$ at the perimeter of a base station's planned coverage for the design value of N_0), then capacity can only be increased as the square root of the bandwidth if σ_t at the end-of-range is to be maintained constant. On the other hand, if there is "margin" designed into the link budget for the base stations, and $E_b/N_0 > x_0$ at the nominal end-of-range, then it could be claimed that T_b could be reduced as the inverse-square of the bandwidth while maintaining σ_t constant at the coverage perimeter. However, doing so simply reduces E_b/N_0 at the perimeter, reducing the margin. The additional capacity is being gained at the expense not only of bandwidth, but also of signal strength margin, which presumably was designed into the system for good reason. Indeed, capacity can also be increased by simply decreasing T_b (and reducing the margin) without increasing the bandwidth, although σ_t at the coverage perimeter will increase.

If the main signal impairment is an interference source of received power I, it could be argued from (14) that the effective noise spectral density is $N_0 = I/B$, so N_0 and hence T_0 decreases with bandwidth. While this is true for a single interference source, there will be numerous interfering Part 15 transmitters, randomly distributed in space and frequency. The greater the receive bandwidth of the AVM system, the greater the number of interference sources per unit area that will fall within the bandwidth. Moreover, as will be seen in the next section, the interference power that can be received from even a single Part 15 device is so high that bandwidth expansion is not a practical means to mitigate it (the impracticality of using bandwidth expansion to overcome the effect of a strong interfering signal is also discussed in Appendix 1 to Teletrac's Comments, pp. 37-38).

4. PROPAGATION AND RECEIVED SIGNAL POWER

4.1 Desired Signal Power

In the mobile radio environment, there often is no line-of-sight path between a vehicle and a base station several miles away, and the signal propagates via reflection, diffraction, and penetration through obstructions. The received signal often is modeled as having a median that varies as $d^{-\gamma}$, where d is the base-to-mobile distance and γ is the path loss exponent. Random large-scale variations due to "shadow fading" and small-scale variations due to multipath[12] are superimposed on the variations in the median due to changes in d.

Models such as that of Hata [10], which is based on data gathered by Okumura [11], predict the median path loss as a function of d given the frequency, antenna elevations, and type of environment (i.e., urban, suburban, rural). Using the Hata model, the median received power (in dBm) can be expressed in the form

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12. The terms "large-scale" and "small-scale" refer not to the magnitude of the signal strength variations associated with these phenomena, but rather to the distances over which the variations occur. In a severe multipath environment, variations due to multipath are quasi-periodic with minima a half-wavelength apart, on average. Conversely, the variations due to shadow fading occur over many wavelengths (typically tens or hundreds of feet).

$$C = P_{TX} - \alpha - 10\gamma\log d + g_B , \tag{17}$$

where P_{TX} is the ERP of the mobile in dBm, g_B is the gain of the base antenna in dB, and α and γ are given by the Hata model; α depends on frequency, antenna elevations, and environment, and γ depends on the antenna elevations.

The following table shows α and γ for various base antenna elevations in the "suburban" environment at 915 MHz, and the median received power for $d = 5$ miles, assuming a half-wave dipole on the base (2.15 dB gain), and a transmit power (from the vehicle) of 1 watt ERP. For an urban area, the median received power levels would be 10 dB lower at this frequency.

h_B(ft)	α (dB)	γ	C, dBm ($d = 5$ mi)
50	128.3	3.72	-122.1
100	123.7	3.52	-116.2
200	119.2	3.32	-110.2
300	116.5	3.21	-106.7
400	114.6	3.12	-104.3
500	113.1	3.06	-102.4

These levels represent the median signal strength that a Teletrac base station would expect to receive from a mobile 5 miles away. As can be seen, the median received signal is on the order of -100 to -120 dBm, depending on the base antenna elevation. The median received signal level varies roughly 9 to 11 dB per octave with d. For example, with $h_B = 200$ ft, halving d to 2.5 miles would increase C by roughly 10 dB, to about -100 dBm.[13]

Assuming the system is engineered for a noise floor of -90 dBm (see p. 9 of Appendix 1 to Teletrac's Comments), then a -25 dB carrier-to-noise threshold would allow the system to operate with a received signal strength of -115 dBm, which gives a range of about 5 to 10 miles, depending on the tower height. In reality, some margin must be allowed for fading effects, but that will be ignored here in the interests of simplicity.

4.2 Interference Power From Part 15 Devices

The path loss between a Part 15 device at street level and several miles from a Teletrac base station can be modeled using Hata's formulas. However, the Hata model does not apply for separations less that 1 km, and microcell propagation models must be considered. Such

13. The variation of C with d is 3γ dB per octave; that is, if d doubles, C decreases by 3γ dB.

models are discussed by Green [12] and by Green and Hata [13], who observe that in some cases (such as on a roadway when a line-of-sight path is present) the "two-path" model gives reasonably accurate results. This model assumes a direct ray and a ground-reflected ray, with the total received field being the complex phasor sum of the two. The reflected ray thus can positively or negatively reinforce the direct ray, depending on the phase relationship between the two. The ground-reflection coefficient can be calculated as a function of the incidence angle, as discussed by Jordan and Balmain [14].

Fig. 6 shows the received power vs. d for h_B = 100 ft, f = 915 MHz, and P_{TX} = 1 watt (the maximum transmitted power for a Part 15 device operating in the 902-928 MHz band under §15.247 of the FCC Rules). The parameters σ and ϵ_r are the conductivity (mhos/meter) and relative dielectric constant assumed for the ground. As can be seen, the reflection causes oscillations of 5 to 10 dB about the free-space (d^{-2}) level, until the "break point" (roughly a mile here) is reached and the received signal begins to drop off as d^{-4}. For distances up to a mile, the received interference power lies between -30 dBm and -60 dBm. Figs. 7 and 8 show similar curves for 200 ft and 400 ft base station antenna heights, respectively. Fig. 9 shows the received signals for all three heights together.

The levels of interference shown by these curves will create a serious problem for receivers such as Teletrac's. To illustrate, assume that receiver coverage boundaries are designed for a noise floor of -90 dBm (i.e., a received signal power of about -115 dBm). A received interference level of -55 dBm, which corresponds to an interference source roughly 4000 feet from the base for a two-path model with h_B = 100 ft, would require an increase of 35 dB in the desired signal level, which would decrease the range by roughly a factor of 10, and the coverage area by a factor of 100. This effectively would remove the base station from service.

Finally, it is reasonable to assume that because of the interference-prone, uncontrolled nature of the 902-928 MHz band, many Part 15 devices will be designed with some degree of frequency agility, to allow them to avoid interference so as to provide their customers with clear communication channels. Unfortunately, such capability will not be of much help in reducing their interference to a system such as Teletrac's, because it depends on the ability to detect an interfering signal. The reverse-link signal in Teletrac's system will emanate from a vehicle near the ground, will be spread over a wide bandwidth, and will be of very short duration. Hence, it is unlikely that it will be seen by the Part 15 device, which will have no way of knowing that the band is "in use," and will therefore have no reason to avoid transmitting in it.

4.3 Effect of Frequency Hopping and Direct Sequence Modulation of the Part 15 Signal

Section 15.247 of the FCC Rules allows Part 15 devices operating in the 902-928 MHz band to use up to 1 watt of RF transmit power providing either direct sequence modulation or frequency hopping is used. The purpose of this subsection is to discuss the effect of these requirements on the potential for interference to Teletrac's receivers.

Direct sequence modulation spreads the transmitted signal power over a bandwidth much greater than the information bandwidth. Section 15.247 requires a "spread" bandwidth of at